Article

New Framework for Assembly Digitalization and Traceability Using Smart Contracts and Bill of Assembly

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Featured Application: Authors are encouraged to provide a concise description of the specific application or a potential application of the work. This section is not mandatory.

Abstract: The final assembly of appliances and automotive industries is a rigorous process, that has limited capabilities of full traceability associated with: (1) the parts installed, (2) their fabrication processes, and (3) the assembly work. This is also the case for each of its sub-assemblies The many parts and sub-assemblies that compose the final assembly, make full traceability a challenging fit, that is almost unsurmountable. Such full traceability along the entire supply-chain is not existent today and must be based on documentation of most assembled parts, assembly tasks, and inspection tasks that compose the full assembled product. In addition, security measures are needed to prevent hostile hacking and unauthorized approach to the assembly documentation throughout the entire supply chain. The related documentation and repeated verifications require considerable effort and have many chances for human errors. So, automating these processes has a great value. This article expounds a framework that harnesses block-chain and smart-contract technology to offer traceable and protected documentation of the assembly process. We expand the concept of a Bill-Of-Assembly (BOA) to incorporate data from the bill of materials (BOM), the associated assembly activities, the associated activities' specification parameters and materials, and the associated assembly resources (machines and/or operators). The paper defines the operation of the BOA with blockchain and smart-contract technology, for attaining full traceability, safety, and security, for the entire assembled product. Future research could extend the proposed approach to facilitate the usage of the BOA data structure in constructing a digital twin of the entire simulated system.

Keywords: Smart Assembly; Smart contract; Assembly line; Assembly 4.0; Assembly system; Blockchain; Digital twin; Industry 4.0; Smart manufacturing

1. Introduction

Assembly of complex products found in various industries (such as the aviation, automotive, medical, and heavy-duty machinery) is extremely complex and involves many thousands of parts and operations, as well as huge amount of human resources and machinery. Controlling, monitoring, and documenting the assembly processes becomes a major challenge. From the supply-chain perspective the challenge is to trace and document the parts, sub-assemblies, and operations, from the bottom level, up to the final assembled product. Safety and security go hand in hand in the production of these assemblies, and even more so for the medical devices industry.

This paper describes a framework for integrating smart contracts into all the stages of the assembly supply-chain to attain full traceability of the product sub-assemblies, parts, and processes. This integration enables automated verifications and authorizations for the many stages of the supply chain and the assembly process. The result is an advanced assembly data structure that could be the backbone of the product's digital twin (DT). The proposed smart contracts are based on a platform of block chain that gives it the

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advantages of immutability and security. For that we propose the concept of Bill-Of-Assembly (BOA) is which incorporates data from the bill of materials (BOM), the bill of operations and processes, and the bill of resources (machines and/or operators).

While the aircraft industry requires strict traceability [1], supply chains of other complex products such as automobiles often lack traceability and documentation. However, legal authorities such as the National Highway Traffic Safety Administration of USA or Federal Motor Transport Authority of Germany, require end-to-end traceability of parts [2].

Zhuang et al. [3] stated that: "The complexity of large assemblies has fostered segmentation and decentralization of production chains and exacerbate their information management. Consequently, interoperability, as well as data integration and exchange, have become a major challenge in discrete assembly processes and induce the need for innovative traceability solutions". To tackle this challenge there were several attempts to use blockchain technology. For example, Wang, et al. [4] used blockchain solution in an aircraft assembly setting. Kuhn et al. [5] developed a decentralized blockchain application called TokenTrail, which focuses on the specific traceability requirements of multi-hierarchical assembly structures. This is an important proof of concept that supports the use of smart contracts as advocated in our paper and in Khan, et al. [6] and Westerkamp et al. [7].

Traceability becomes crucial for the identification of defective parts in recalls, and even more so, when multiple suppliers are involved [8]. Defective parts must be rapidly identified among massive number of vehicles. The prohibitive cost of manual investigation in such cases increase the attractiveness of automating the traceability [2]. Another challenge is the detection of counterfeit parts, especially in after-sales markets [8,9]. Dasaklis et al. [10] suggested a framework for supply chain traceability based on blockchain tokens. However, they did not use the approach as suggested here.

BOM documentation is the core data structure in the entire life cycle of assembled products. When the BOM contains enough information, it could be the primary data source for any investigation. The investigation can focus on the part, or on sub-assemblies, or processes, whether for knowledge extraction, or for simulation [4]. Therefore, in our proposed model we adopt the approach of centralizing the development of product data around the BOM. However, in complex assemblies such as aircraft assembly, there are many thousands of parts and processes, that complicate the construction of a unified BOM [11]. In some domains there are very different versions of BOMs: engineering BOM, static service BOM (SBOM) [12], process BOM (PBOM), manufacturing BOM (MBOM), and maintenance BOM (WBOM) [4].In these cases, it is obvious that constructing a unified BOM is a considerable challenge [11]. We do, however, propose a unifying approach so that the product will have a single unique documentation database. In our proposed unified approach, we heavily deploy smart contracts as a mechanism for automating validation and enabling reliable traceability.

Smart contract are contract paragraphs written in computer programs [13]. Smart contracts are automatically implemented when prerequisites are met, thus preventing human errors. Smart contracts automatically perform transactions, and are stored, replicated and replaced (if needed) in distributed ledgers [14]. To attain the trust of all stakeholders of the assembled product the contracts must be decentralized programs cryptographically protected with verified immutability. The straightforward application of such smart contract must operate as on a blockchain network [15]. To attain the immutability (prevent tampering with the code), smart contracts should be copied to each node of the blockchain network [5]. It was also validated using a case-study presented by Eryilmaz et al. [16].

In the proposed framework, in each stage of the assembly the smart contracts will contain prerequisites of verifying the traceability of the assembled components and subassemblies. Only after the verification the smart contracts will enable to insert their data into the product documentation. In that way, overall traceability is maintained with full documentation.

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The paper continues as follows: section 2 describes the proposed Bill of Assembly (BOA) and the process of its generation. Section 3 focuses on the integration of smart contracts for constructing the BOA. Section 4 discusses the advantages and frailties of the proposed BOA and its construction method. Section 5 concludes the paper with the main conclusions and future research potential.

2. BILL OF ASSEMBLY (BOA)

Current research already proposes to extend the assembly data and infer processes from BOMs. Ebrahimi & Åkesson [17] extract data from the BOM to find assembly sequences feasibility. Yunitarini & Widiaswanti [18] proposed an integrated computer aided process planning (CAPP) and BOM. The process planning is based on the BOM, since before planning the assembly processes on a workpiece or a part, the assembler must know the parts and process specifications and product structure. Cohen et al. [19] extended the BOM to BOA and the current paper expands on their approach. Wang and Li. [4] introduced the reconstruction process of the BOM, and the BOM consistency reconstruction mechanism of complex products. This extended BOA is then used for generating a digital twin. The reconstruction process affects the whole framework of their proposed method, and it is very different then constructing the digital twin simultaneously with the physical construction, which is the subject of this paper. Kuczenski et al. [20] demonstrate the solution to the problem of assembly product design and redesign by developing a distributed software. The results demonstrate that the problem of automated product system models (PSM) construction is achievable.

The proposed BOA.

The proposed BOA is depicted in figure 1 and is composed of the following information:

- The BOM – includes information regarding to the assembly structure
- Part parameters (from engineering BOM) – includes information regarding to the sizes and features that characterize each of the parts in the BOM
- Assembly activities (from the PBOM) their times and precedence relations – related to the BOM
- Manufacturing activities (from the MBOM) the machines, tools and manufacturing processes and their parameters.

In figure 1 the final assembly is composed of three sub-assemblies (S.A.1, S.A.2, S.A.3), and sub-assembly 1 is composed of two sub-assemblies (S.A. 1.1, S.A. 1.2) and their raw materials (RM1,…RM4). The shaded part (in grey) of S.A. 1.1 denotes the completed assembly activities related to S.A. 1.1. Sub-assembly 1.1 (S.A. 1.1.) is further described using activity precedence diagram, in an exploded view at the bottom of figure1. The completed activities are shaded in grey. The processing of each sub-assembly requires the automatic verification of the identity of all its parts using smart contracts. At the lower level of parts and row materials, a smart tag (hardware chip) has to be scanned for identity verification. At higher levels, the smart contracts of the lower level communicate the completion of their sub-assemblies, to the smart contract related to the higher level. This hand-off process requires cryptographic verification of the smart-contract identity between levels.

As could be seen in figure 1, the BOM is the basis for the proposed BOA of each product (workpiece) and the backbone for the additional information. The novelty of the proposed additions to the BOM is encapsulated in an extended activity diagram associated with each subassembly in the BOM, detailing all its processes and parameters (example is depicted in figure 1 for S.A. 1.1). Assembly lines are characterized by an evolutionary assembly of its final product as the main workpiece flows through the workstations. We define the workpiece (WP) to be the main product in process, meaning that it is the main product part in its evolution.

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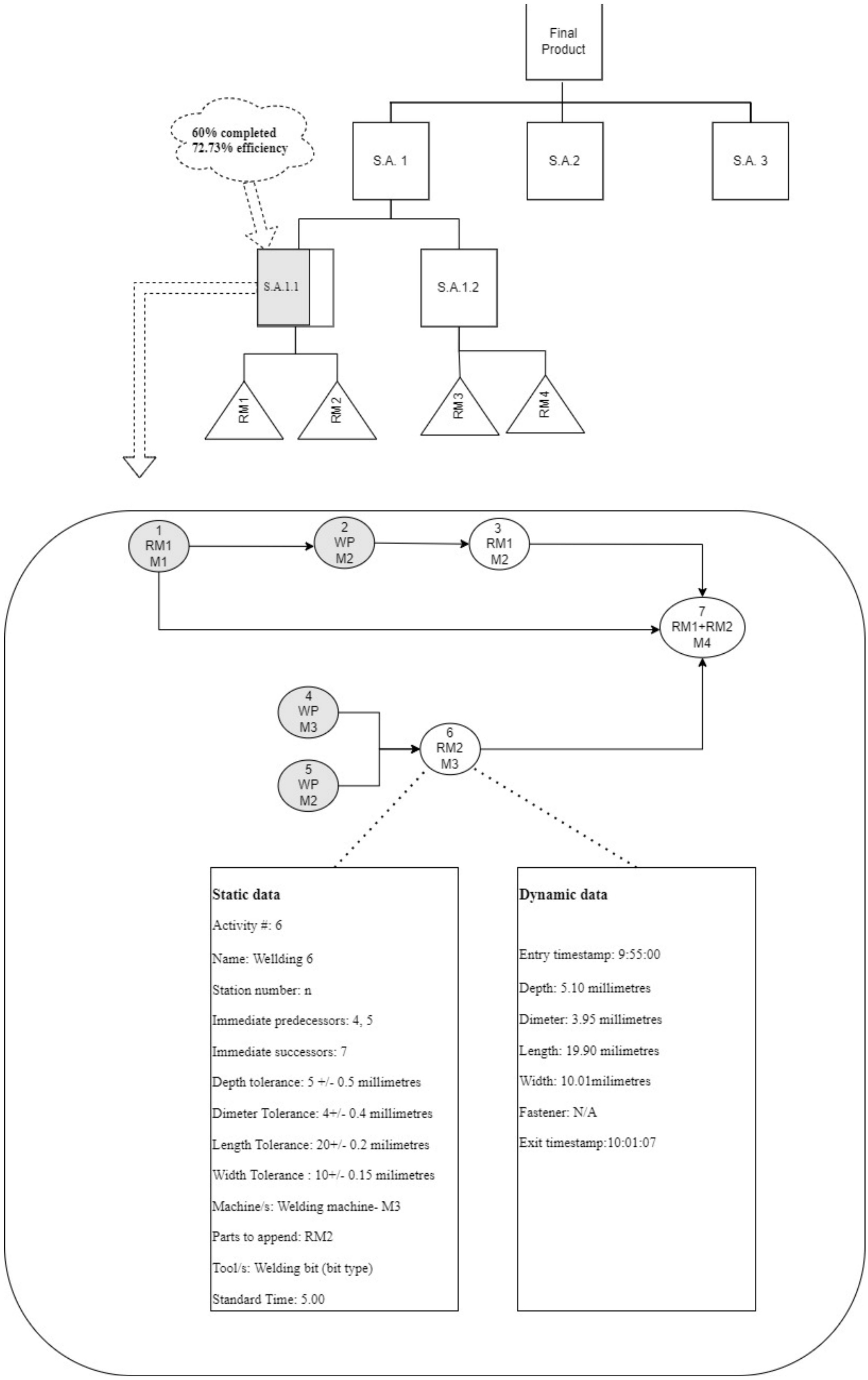

Figure 1. Bill of Assembly (BOA)Example: Exploded view

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While regular activity diagrams have precedence constraints between nodes and activity times, the proposed diagram have additional information on: (1) the processed material or subassembly, (2) the machine or tool used at each activity, (3) activity static information, and (4) activity dynamic information (workpiece related).

These are very important additions of information to the regular precedence diagrams. Our proposed scheme includes the smart-contract verification of the compliance of dynamic data to the static data. We use figure 1 for illustrating the verification. In figure 1, the static data specify that the activation of task 6 is dependent on the completion of tasks 4 and 5. The suggested role of the smart contract is to verify these completions by monitoring them, before allowing activity 6 to begin. Activity 6 generated the various measures. These measures are compared against the static data ranges of each parameter. Thus, the verifications related to figure 1 are as follows:

1. **Depth**: dynamic measure = (5.1), static range = depth (4.5-5.5), Verification result: Compliance
2. **Diameter**: dynamic measure = (3.95), static range = diameter (3.6-4.4), Verification result: Compliance
3. **Length**: dynamic measure = (19.90), static range = length (19.8-20.2), Verification result: Compliance
4. **Width**: dynamic measure = (10.01), static range = width (9.85-10.15), Verification result: Compliance

Two important parameters for each activity are: the standard time estimation (static data for an activity) and actual activity time measure (dynamic data). Activity 6 finishes at time: 10:01:07 – this is a dynamic timestamp that enables the computation of the actual process time by comparison to the start time: 10:01:07-09:55:00 = 6:07 minutes, this could be compared to the standard time of 5 minutes and give the efficiency of 5/6:07=0.817=81.7%.

The actual activity time for each workpiece is computed as the subtraction of the entry timestamp from the exit timestamp of the workpiece. This additional data as well as all BOA data must be directly accessible to the organization data systems.

To assess the efficiency for each sub-assembly, the standard times of all the activities are summarized for all assembly operations of that subassembly, to form its expected time. The availability of standard times, and timestamps at the workpiece entrance and exit, allow to track the efficiency of the assembly processes at any time during the production. Also, these data enable to track the inefficient waiting times for parts and sub-assemblies. This information has not been part of any analytical tool so far. To illustrate this point, we use an example: The construction of sub-assembly 1.1 is done using 7 activities with 7 standard times and indication of two row materials (RM1, RM2) as shown in Table 1:

Table 1. Activity property descriptions

Activity Num.	Standard Duration (Minutes)	Workpiece (WP) and/or Row Material Num. (RM#)	Machine Num. (M #)
1	2	RM1	M1
2	3	WP	M2
3	1	RM1	M2
4	4	WP	M3
5	3	WP	M2
6	5	RM2	M3
7	3	RM1, RM2	M4

The sum of the standard times of all S.A.1.1 activities is: 2+3+1+4+3+5+3 = 20
Now we measure at each activity ending time the actual time it was performed.
For example, suppose activities 1,2, 4, 5 were completed as follows:
Activity 1: 3min, 150% of standard (2 min)
Activity 2: 4 min, 133% of standard (3 min)
Activity 4: 5 min, 120% of standard (4 min)
Activity 5: 4.5 min, 150% of standard (3 min)
So, the completed standard work (for activities 1, 2,4,5) is: 2+3+4+3 =12
out of 20, 12 is 60% of total standard time for S.A 1.1
The actual execution time (activities 1, 2,4,5) is: 3+4+5+4.5 = 16.5 Min (see figure 2).
The efficiency of the execution time (as shown in figure 2) is: 12/16.5 = 72.73%.

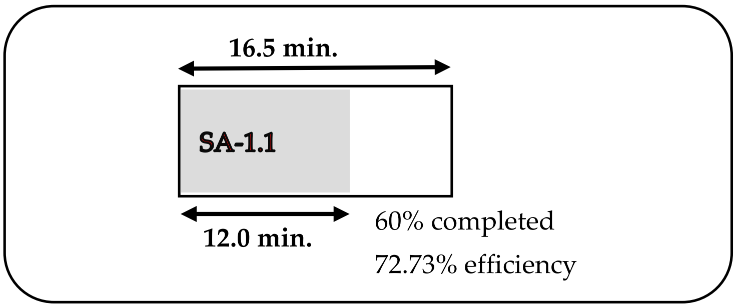

Figure 2. Illustration of the subassembly 1.1 efficiency computations

The BOA system is also storing historical documentation of the efficiency, and other measures in the recent time window (rolling horizon). This data enables the analysis and the discovery of trends that require intervention and maintenance.

Advantages of the BOA implementation based on smart contracts:

- Automated verification of part ID
- Automated verification of accumulated data
- Intuitive data structure
- Embedded quality control via smart contracts
- Automated measures documentation and efficiency measures reporting

Downsides of the BOA implementation based on smart contracts:

- Rigid structure that does not allow changes
- The verification is complicated and sophisticated
- The smart contracts need explicit definition of alternative parts and sub-assemblies
- The smart contracts are not-forgiving even for minor and acceptable deviations form specifications.

3. INTEGRATING SMART CONTRACTS IN BOA

In this section we first discuss the current state of the art in the deployment of smart contracts in logistics and supply chains. We then discuss the implications and describe our suggested method for using the smart contract in the process of building the product BOA. For reliable traceability, the smart contracts should be applied throughout the entire supply chain process. At the end of the production process the final assembly requires intense application of smart contracts. At this stage the BOA is developed along the assembly line, and therefore must be controlled by the assembly-line's stations.

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The use of smart contracts in logistics and supply chains has gathered interest and experience in recent years, asserting the ability of smart contracts to provide traceability in various supply chains in different industries. The following cases are just sample from the literature on this subject. Seifermann et al. [21] developed requirements for tracking and tracing using blockchain technology. They present a model that has been implemented in a Proof-of-Concept for traceability and tracking using smart contracts in the Ethereum blockchain. Kuhn et al. [5] developed a decentralized blockchain application that meeting rigorous traceability requirements of various assembly products and sub-assemblies. Their application combines Ethereum network and a Proof of Authority consensus. The traceability is supported by special tokens that combine cryptography, and data of complex assembly processes and structures. Casino et al. [22] presents a case study in the dairy sector of Blockchain-based food supply chain traceability. They implement a set of functions to provide an end-to-end traceability flow, from raw materials acquisition to end customers product delivery.

The suggested method starts at the very beginning of the supply chain by verification of the raw materials. In case the raw materials are produced by automated machines, the verification could be done as part of the automated process by the attachment of smart tags (with cryptographic shielding layer). In case the process is not automated the smart tag authorization involves the people in charge (and their identity verification). From this point on, the verifications along the supply chain could and should be done by smart contracts. This automates the verification process and provides secure traceability.

For each sub-assembly, there is a separate smart contract having the information about the structure of the sub-assembly, and its precedence activities. For a given sub-assembly, the smart contract detects the availability of the sub-assembly components via scanning (e.g., RFID tags could be scanned with antennas [23]). Of course, the smart contract must verify the authenticity of the parts (checking the cryptography), and their complacency with the technical requirements of the subassembly.

In figure 3 we describe the verification logic of the smart contract related to activity 6 from figure 1.

Figure 3 main process starts after the arrival of the workpiece at the workstation where activity 6 is performed. This arrival invokes the verification agent of activity 6. At the beginning the agent of activity 6 is waiting for the completion tokens of predecessor activities 4 and 5 to initiate the smart contract verifications. The arrival of tokens 4 and 5 starts the verification process: first the tokens authenticity is verified, then the operator identity is verified, then the raw-material authenticity and type are verified, them the machine type and its suitability are verified. If all the verifications were successful, activity 6 is authorized and timestamp is recorded. Activity 6 starts formally at this moment and the static parameters relevant to Machine 3 are inserted by the smart contract code. Next, the processing stage is performed and at the end of the processing the measures are taken for all the relevant parameters (e.g., depth, diameter, length, width). The actual measures are compared to the static data and a decision is made about their compliance. If all measures were found compliant, activity 6 is cleared for completion and termination. A timestamp is recorded, and a token of the completion is distributed and transferred to the succeeding activities.

4. DISCUSION

The data accumulation along the assembly process of each product is a gradual process. But even before each product is produced its static data is already available. The static data is derived from the product development and design, as well as the assembly production plans for each product. This is the standard data of the product structure, the related assembly activities, and their (the product structure, and assembly activities) specifications.

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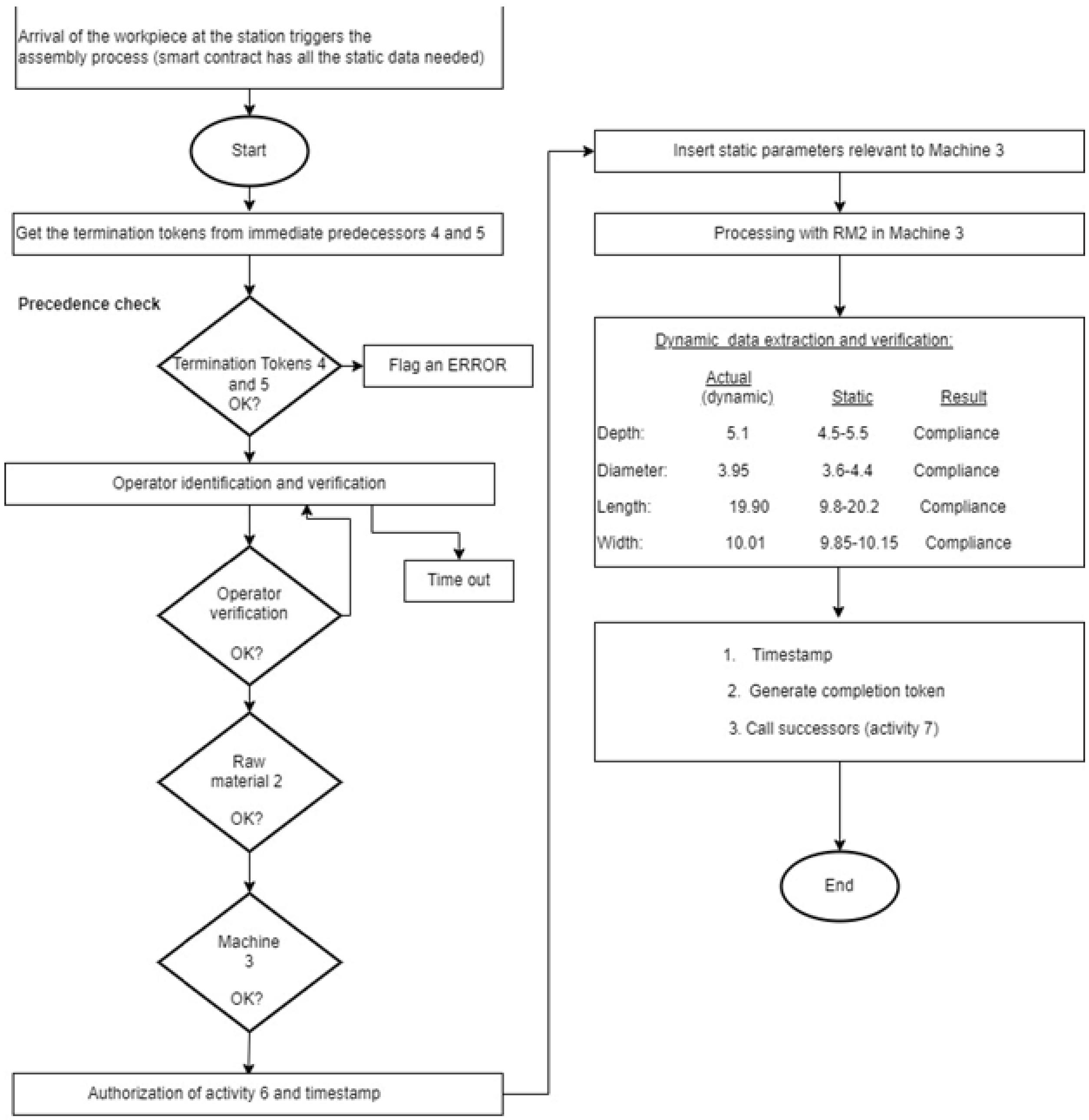

Figure 3. Verification logic of the smart contract related to activity 6 (see figure 1)

The dynamic data is the data that comes with the actual raw-materials, assembly activities and the sub-assembly measured parameters. Thus, the verification processes only need to compare the static and dynamic data. In other words, if the data collection and the verifications, and authorizations would be automated, the whole control process could also be automated. We, therefore, suggest doing exactly this by using smart contracts.

Smart contracts are open-source programs readable by humans and executes automatically, exactly as implemented. They are usually, protected by both cryptography and wide distribution (much like block-chain practices), rendering them as immutable. This makes them immune to fraud, counterfeit, or censorship [24] . These characteristics make

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smart contract the technique of choice when traceability is needed. This section discusses the ways to apply the smart contracts in the proposed framework.

One of the key issues is the verification of the raw-materials and sub-assemblies for traceability purposes. We first focus on fundamental parts (and raw materials). These parts should have an attached identifier such as RFID tag [23] , a microchip, or a small IoT enabled sensor [25]. A much less attractive option would be a bar-code. Some, cryptographic rule should be incorporated into these identification tags to authenticate the part identity, and its embedded data. Some discrete data must be shared between the suppliers along the supply-chain in order the facilitate the smart contract process. Once the parts are authenticated and verified, the subassembly containing them would carry on the verification process as described in previous section.

To enable traceability through the whole supply-chain the various links in the chain must be coordinated seamlessly to enable smooth operation of the smart contracts. This require them to be part of the distributed ledger that the smart contracts use, to coordinate some passwords for authentication, and have communications channels to be able to communicate with each other.

The proposed technique has the potential to automate large part of the assembly process dedicated to verification and control. This is especially crucial in certain industries where regulations require high level of traceability such as the food, pharmaceutical, spacecraft and aircraft industries [1] .

The proposed framework has its own limitations. First it requires high level of computerized environment through the entire supply-chain. Second, it requires close coordination between the various links in the supply chain. Third, any deviation from the preplanned smart contract is very difficult to handle as a new smart contract would be required (usually involving and requiring the consent of two or more organizations in the supply chains). Fourth, any change in the static data has to be made before the product is assembled. Finally, we did not delve into the scenarios where the verification or authentication fails, but in such cases the automated advantage of the proposed system fades.

The proposed BOA data structure could be a main core of a digital twin data base. At the end of the assembly line the BOA is a full documentation of the AS-BUILT BOM, and many other parameters. This includes the sensors and sub-assemblies of the full product. This is however still far from being the actual digital twin that emulates the behavior of the product under different scenarios. The mutual effects of the sub-assemblies on each other, is the first additional necessary layer to be added to the BOA (e.g., in automotive industry a car cooling system if operated cools the engine). Then the effect of the controls over the various sub-systems is a second added layer (e.g., pressing the beak pedal activates the braking system and the breaks). Finally, the effect of some of the product parts on the environment (and vice versa) is the third layer (e.g., the wheel, which is locked by the breaks, has an intensive friction force on the road, which halts the car). So, with these additional three layers, the foundations of a digital twin are ready for simulation.

5. CONCLUSIONS

In this paper we describe a full framework that supports automated traceability throughout the supply chain, for a given assembly process. This issue is usually challenging, as lots of documentation and verification stages are required. The related documentation and repeated confirmations, authorizations, and certifications, require substantial effort and have numerous chances for human errors, so digitalization and automation of these processes has a great value. To facilitate this digitalization, we proposed the extended bill of assembly (BOA) as the backbone of the traceable documentation of each assembled product. For automating the entire control and documentation process, we suggested a framework that uses smart-contract technology with the extended BOA. This

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framework offers traceable and protected documentation of the assembly process, providing security, safety, and full traceability, for the full assembled product. In other words, the proposed framework provides security measures needed to prevent counterfeit parts, hostile hacking, and unauthorized approach to the assembly documentation throughout the entire supply chain. Moreover, using the proposed framework, with a smart contract for each assembly activity automates the control, documentation, authorization, and certification activities throughout the entire assembly process.

Future research may be pursued in several directions: (1) performing case studies to validate and improve the suggested framework. (2) extending the proposed approach to facilitate the usage of the BOA in constructing a digital twin (section 4 briefly discusses this option). (3) Using the BOA accumulated data of each product, in a shopfloor, to better plan and schedule the assembly process.

Declarations

Author Contributions: Conceptualization, Y.C. and S.R.; methodology, Y.C and S.R.; validation, S.R.; formal analysis, Y.C.; investigation, S.R.; writing—original draft preparation, Y.C and S.R.; writing—review and editing, Y.C and S.R.; visualization, S.R. All authors have read and agreed to the published version of the manuscript.

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